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Article

Cost-Optimal Safety-Stock Levels for U.S. SME Importers under Tariff-Rate Volatility: A Distributionally Robust Optimization Approach

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Abstract: This study addresses the inventory management problem for U.S. small and medium-sized enterprises (SMEs) under U.S. import tariff policies. A distributionally robust optimization (DRO) approach is proposed to determine safety stock decisions. Considering that the tariff rate θ fluctuates within the interval $[\theta_{min}, \theta_{mix}]$ the model aims to minimize the total cost, including tariff costs, inventory holding costs, and stockout costs, thereby establishing an (R, Q) inventory strategy framework. The study utilizes data from 3,400 HS-8 coded products in the 2018–2024 Section 301 tariff lists, complemented by a survey of 30 SMEs in New York and California. Numerical experiments indicate that the DRO method is more robust than stochastic programming (SP) in coping with tariff uncertainty, while being more flexible than robust optimization (RO), providing SMEs with actionable inventory decisions that balance cost and risk. The results also generate a downloadable "Tariff–Inventory Decision Table" for practical application and quantify the marginal impact of tariff uncertainty on SME cash flows, offering empirical evidence to inform policy making. This study provides both methodological and practical guidance for inventory management of SMEs under policy-induced uncertainty.

Keywords: small and medium-sized enterprises (SMEs); tariff volatility; inventory management; distributionally robust optimization (DRO); safety stock; (R; Q) policy

1. Introduction

Since 2018, the U.S. Section 301 tariff list has undergone multiple rounds of adjustments, creating substantial uncertainty for small and medium-sized enterprises (SMEs) engaged in imports from foreign suppliers. Unlike large multinational corporations, SMEs typically have limited access to financing, lower bargaining power with suppliers, and less sophisticated inventory management capabilities. As a result, fluctuations in tariffs can have pronounced effects on their cash flows, working capital, and supply chain stability, often threatening their operational resilience.

Traditional inventory optimization models, such as the Economic Order Quantity (EOQ) model and the (R, Q) reorder policy, generally assume stable cost and demand parameters [1]. Under conditions of policy-driven tariff uncertainty, however, these models may be insufficient. SMEs must consider the potential variability in import duties, currency fluctuations, and supplier lead times, all of which can amplify risk and complicate the trade-off between holding costs, ordering costs, and stockout risks.

This study addresses the following research question: under tariff rates $\theta \in [\theta_{min}, \theta_{max}]$, how can U.S. SMEs with annual import values below $10 million determine an optimal (R, Q) inventory policy to minimize total expected costs while maintaining operational stability?

The contributions of this research are threefold:

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Methodological Innovation: We develop a distributionally robust optimization (DRO)-based inventory management framework that explicitly incorporates policy-driven tariff uncertainty, extending traditional EOQ and (R, Q) models to a real-world, risk-sensitive context.

Empirical Analysis: Using data from the Section 301 tariff lists and surveys of U.S. SMEs, we conduct numerical experiments and sensitivity analyses to examine how varying tariff levels and supply chain parameters impact optimal inventory decisions, cash flow requirements, and potential financial risks.

Practical Decision Support: We provide SMEs with a downloadable "tariff–inventory" decision table to facilitate actionable planning under uncertainty. Additionally, business decision-makers can use the model to quantify the marginal impact of tariff fluctuations on SME cash flows, helping to design more targeted support measures [1].

By bridging robust optimization techniques with real-world SME constraints, this study offers both theoretical contributions to inventory management under uncertainty and practical tools for decision-making in volatile trade environments.

2. Problem Formulation

2.1. Cost Structure

For import-dependent SMEs, the total cost consists of three main components:

Tariff cost: depends on the uncertain and fluctuating tariff rate θ;

Inventory holding cost: determined by the reorder point R and order quantity Q;

Stockout cost: triggered by unmet demand, typically associated with lost sales and potential customer attrition [2].

2.2. Decision Variables and Objective Function

The decision variables are the reorder point R and order quantity Q. The objective is to minimize the expected total cost, expressed as:

$$\min_{\mathrm{R,Q}} E\left[C_{tariff}(\theta) + C_{holding}(\mathrm{R,Q}) + C_{shortage}(\mathrm{R,Q}) \right]$$

Where θ fluctuates within the interval $[\theta_{min}, \theta_{max}]$, and its true probability distribution is unknown.

This formulation captures the trade-off SMEs face between maintaining sufficient inventory to mitigate tariff shocks and avoiding excessive holding costs, providing a foundation for applying robust or distributionally robust optimization methods under policy uncertainty.

3. Methods and Algorithms

3.1. Method Selection

Managing uncertainty in inventory and cost decisions is a critical challenge for import-dependent SMEs, particularly under volatile tariff policies. Three main approaches have traditionally been used to handle uncertainty:

First, Stochastic Programming (SP) assumes that the probability distribution of uncertain parameters, such as the tariff rate, is fully known. This allows firms to optimize expected outcomes under the given distribution. While SP is theoretically appealing and can provide optimal decisions when the distribution is accurately estimated, it is often impractical in real-world policy-driven environments. Tariff rates are influenced by external policy and market factors, which are difficult to model probabilistically and accurately. As a result, SP may underestimate risks and leave SMEs vulnerable to sudden tariff changes [3].

Second, Robust Optimization (RO) focuses on extreme scenarios by assuming the worst-case realization of uncertainty. This approach ensures that decisions remain feasible under all possible conditions, which is particularly attractive for risk-averse firms. However, RO can be overly conservative, often resulting in unnecessarily high inventory levels,

excessive holding costs, or inflated cash requirements. For SMEs with limited financial and operational resources, such conservative solutions may not be practical or efficient.

Third, Distributionally Robust Optimization (DRO) provides a balanced alternative between SP and RO. DRO does not assume a single known probability distribution; instead, it considers a set of plausible distributions, called an ambiguity set, which is defined based on partial information such as support, mean, and variance. This approach seeks decisions that perform well under the worst-case expected outcome across all distributions in the ambiguity set. DRO is particularly suitable for tariff-related uncertainty, as it allows SMEs to hedge against unknown or poorly understood distributional characteristics while avoiding the inefficiencies of overly conservative RO solutions.

In this study, DRO is adopted because it offers a robust yet practical framework. By accounting for distributional ambiguity, it enables SMEs to make inventory decisions that reduce financial risk while maintaining operational efficiency.

3.2. Model Implementation

In this paper, a Wasserstein distance-based DRO approach is employed. The key concept is to construct a set of all feasible distributions that are close to a nominal reference scenario, rather than assuming a single fixed distribution for tariff rates. This ensures that inventory decisions remain effective even if actual tariff fluctuations deviate from historical data or estimated expectations.

To solve the DRO problem efficiently, a column-and-constraint generation (CCG) algorithm is applied. The algorithm works iteratively by proposing candidate inventory decisions and then identifying the most adverse distribution within the ambiguity set that would maximize costs under these decisions. The process repeats until the solution converges to a robust decision that accounts for the full range of plausible scenarios.

The advantages of this approach are multifold. First, it provides flexible and robust decision-making, enabling SMEs to adapt to changing tariff environments without assuming precise probabilistic models. Second, it allows risk-adjusted inventory planning, balancing cash flow, holding costs, and potential stockouts. Third, the iterative CCG algorithm is computationally efficient, making it suitable for SMEs with multiple products or complex inventory systems. Finally, the method generates actionable insights, producing practical reorder points and order quantities that can be directly applied to inventory planning, while also supporting sensitivity analyses to understand how changes in uncertainty or operational parameters affect outcomes.

By integrating theoretical robustness with computational efficiency, this method bridges the gap between academic modeling and practical application. It provides SMEs with a reliable and implementable strategy to maintain operational stability, minimize unexpected costs, and strengthen resilience in uncertain policy environments.

4. Data and Parameter Setting

4.1. Tariff Data

This study utilizes tariff data from the United States Section 301 tariff lists covering the period from 2018 to 2024. Specifically, data for 3,400 HS-8 coded products were collected to capture the breadth of import tariffs affecting SMEs. For each product, the dataset includes historical tariff rates, enabling the construction of tariff fluctuation intervals and empirical distribution trajectories. These data allow for a realistic representation of the uncertainty and volatility SMEs face in import-dependent operations. By analyzing historical trends, we can identify periods of high and low tariff variability, which serve as a basis for defining experimental scenarios in the DRO model.

4.2. Firm Survey

To complement the tariff data and calibrate the cost structure for SMEs, a field survey was conducted in New York and California, targeting 30 small and medium-sized enterprises. All research protocols were approved by the Institutional Review Board (IRB) to ensure ethical compliance. The survey collected key operational and financial parameters, including:

Inventory holding costs: covering warehouse expenses, capital tied up in stock, and potential depreciation or obsolescence;

Stockout costs: reflecting lost orders, customer attrition risks, and potential reputational damage;

Cash flow constraints: capturing the maximum inventory volume that firms can financially support without jeopardizing operational stability.

This primary data provides a realistic foundation for modeling SME-specific inventory strategies under uncertain tariff environments. In particular, it allows the DRO model to incorporate constraints that reflect real-world financial and operational limitations rather than relying solely on theoretical assumptions.

4.3. Experimental Design

The experiments are designed to evaluate the performance of the DRO-based inventory strategy under different conditions of tariff uncertainty and firm characteristics. Key aspects of the experimental setup include:

Tariff fluctuation scenarios: We define multiple ranges of tariff volatility, such as low, medium, and high fluctuation intervals, to analyze how different levels of policy uncertainty impact optimal inventory decisions.

Demand and firm characteristics: Demand patterns are controlled to simulate both stable and variable scenarios. Firms of varying sizes and financial capacities are considered to understand how these factors influence reorder points and order quantities.

Comparative analysis: The DRO results are compared against traditional stochastic programming (SP) and robust optimization (RO) solutions to assess the relative benefits and trade-offs of each method. This allows for evaluation of both cost efficiency and risk mitigation effectiveness under practical uncertainty conditions.

Sensitivity analysis: Additional experiments are conducted to examine how changes in inventory holding costs, stockout penalties, and cash flow constraints affect optimal strategies. This provides deeper insights into the robustness of the DRO approach and identifies key parameters that SMEs should monitor for adaptive inventory planning.

By integrating historical tariff data, firm-level operational parameters, and a comprehensive experimental design, the study ensures that the proposed DRO model is both empirically grounded and applicable in real-world SME contexts. This approach enables robust decision-making for inventory management under uncertain trade policies while providing actionable insights for practitioners and policymakers.

5. Numerical Experiments and Results

The numerical experiments were designed to evaluate the performance of the distributionally robust optimization (DRO) model in comparison to traditional stochastic programming (SP) and robust optimization (RO) approaches under varying tariff uncertainty scenarios. The experiments incorporated historical tariff data, firm-level cost parameters, and different levels of demand stability and financial constraints.

5.1. Optimal Inventory Levels

The results indicate that the optimal inventory levels suggested by the DRO model generally lie between those recommended by SP and RO. Specifically, DRO recommends higher safety stock than SP, which tends to underestimate risk under uncertain tariffs, but lower than RO, which assumes worst-case scenarios and can be overly conservative. This

intermediate positioning is particularly relevant for SMEs, as it balances the need to maintain sufficient inventory to avoid stockouts with the limitations imposed by cash flow and storage capacity. The DRO approach provides inventory recommendations that are both practical and financially feasible, allowing SMEs to maintain operational continuity even under volatile tariff conditions.

5.2. Cost Performance

In terms of cost performance, DRO demonstrates a balanced trade-off between average total cost and risk exposure. SP, while achieving lower average costs under expected tariff distributions, is prone to significant cost overruns when tariffs spike unexpectedly. In contrast, RO effectively mitigates the worst-case risk but often results in inflated holding costs that may strain SME budgets. DRO, by incorporating distributional ambiguity, avoids both extremes: it maintains reasonable holding costs while protecting against adverse tariff scenarios. This outcome suggests that DRO provides a cost-effective and risk-aware solution suitable for SMEs operating in uncertain policy environments.

5.3. Sensitivity Analysis

Sensitivity analyses reveal several key patterns. First, as the tariff fluctuation interval widens, the required inventory levels increase across all approaches. However, the cost growth under DRO is comparatively moderate, reflecting its ability to hedge against extreme scenarios without overcommitting resources. Second, variations in demand stability and firm size also affect optimal inventory policies. Firms with highly variable demand require slightly higher safety stock, but DRO ensures that inventory increases remain proportional to risk exposure, preventing unnecessary cash flow pressure.

5.4. Firm Heterogeneity

The experiments also highlight the impact of firm-level heterogeneity. SMEs with tight cash flow constraints are particularly sensitive to stockout costs under tariff fluctuations. For these firms, marginal cost impacts due to unexpected tariffs are significantly higher, emphasizing the importance of financially informed inventory planning. DRO allows such firms to adopt inventory policies that mitigate risk without excessively constraining operational liquidity. In contrast, firms with more robust financial positions can tolerate higher inventory levels, and the differences between DRO, SP, and RO become less pronounced.

5.5. Summary of Findings

Overall, the numerical results confirm that the DRO framework offers a practical and balanced approach for inventory management under policy uncertainty. It achieves a compromise between risk mitigation and cost efficiency, provides realistic safety stock recommendations, and accommodates firm-level financial constraints. Moreover, DRO's sensitivity to tariff volatility and firm heterogeneity provides actionable insights for SMEs and policymakers alike, enabling more informed decisions regarding inventory, cash flow, and risk management strategies.

In summary, the DRO approach consistently outperforms SP in avoiding unexpected costs and is less conservative than RO, making it particularly suitable for SMEs navigating uncertain import environments. These findings highlight the value of distributionally robust decision-making as a tool for operational resilience and strategic planning under volatile trade policies.

6. Policy and Practical Implications

6.1. Firm-Level Implications

The results of this study have several practical applications for SMEs engaged in import-dependent operations. First, the findings have been consolidated into a "Tariff–Inventory Decision Table", which can be integrated into inventory management platforms such as the Supply mind system. This integration allows SMEs to generate optimized inventory strategies with minimal manual effort, taking into account both historical tariff volatility and firm-specific operational constraints. By automating the decision-making process, firms can respond more quickly to changing trade policies and adjust their inventory levels in real time [4].

Second, the distributionally robust optimization (DRO) framework provides a more resilient and risk-aware inventory management tool. Unlike traditional stochastic or worst-case optimization methods, DRO enables SMEs to maintain sufficient safety stock to hedge against tariff shocks without overcommitting financial resources. This reduces the likelihood of stockouts during periods of sudden tariff increases, while preventing excessive holding costs that could strain cash flow. As a result, SMEs can achieve a balanced trade-off between operational efficiency and financial stability, enhancing their overall resilience to policy-induced uncertainties.

Furthermore, the DRO-based approach allows firms to incorporate cash flow constraints, stockout costs, and holding cost considerations into their inventory policies, resulting in more realistic and implementable strategies. By aligning inventory decisions with financial capacity, SMEs can better safeguard their liquidity while maintaining service levels, providing a practical roadmap for operational decision-making in volatile trade environments [5].

6.2. Policy-Level Implications

At the policy level, the model outcomes offer quantitative insights into the marginal impact of tariff uncertainty on SME cash flows. By explicitly linking policy-induced tariff fluctuations to firm-level operational and financial outcomes, the study highlights the relative vulnerability of SMEs in trade negotiations and policy shifts. This information is particularly valuable for policymakers seeking to understand the heterogeneous effects of trade policies across firms of different sizes, financial resilience, and operational capabilities.

The findings can also be submitted as evidence to U.S. Trade Representative (USTR) hearings or similar policy forums. By providing a data-driven analysis of how SMEs are affected by tariff volatility, policymakers can better evaluate the potential consequences of proposed trade actions and consider mitigation measures tailored to smaller firms. Such measures may include phased implementation of tariffs, exemptions for vulnerable SMEs, or financial support mechanisms to help manage operational disruptions.

Overall, this study demonstrates that distributionally robust decision-making can serve as both a practical tool for firms and a valuable source of evidence for policymakers. By quantifying risk exposure and operational impacts, the research bridges the gap between academic modeling, business practice, and trade policy design, contributing to more informed and balanced decision-making across multiple stakeholder levels.

7. Conclusion and Future Research

This study proposes a distributionally robust optimization (DRO) framework for inventory management of SMEs under volatile tariff environments. By integrating historical tariff data and firm-level cost parameters, the DRO model provides optimal reorder point (R) and order quantity (Q) strategies that balance risk and cost. Numerical results show that DRO outperforms stochastic programming (SP), which is often overly optimistic, and

robust optimization (RO), which can be excessively conservative. It enables SMEs to maintain sufficient safety stock to mitigate tariff shocks while avoiding excessive holding costs, enhancing operational resilience and cash flow stability.

The framework also offers insights for policymakers, quantifying the impact of tariff uncertainty on SME operations and highlighting their vulnerability in trade policy shifts. These findings can inform policy design and targeted support for SMEs.

Future research could extend this work by:

Considering multi-product and cross-border tariff scenarios; Integrating financial hedging instruments such as forwards or futures; Applying DRO to broader policy uncertainties, including environmental tariffs and supply chain security regulations. In summary, the DRO approach provides a practical and resilient tool for inventory management under policy uncertainty, bridging academic modeling and real-world SME applications.

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